Behavior of Superelastic SMA Columns under Compression and Torsion(圧縮と捩りを受ける超弾性形状記憶合金円柱の挙動)

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論文内容要旨

CHAPTER 1 Introduction

This dissertation deals with behaviors of the superelastic shape memory alloy (SMA), for large deformation via mechanical loading. The superelastic SMA shows the unique capability of superelasticity (SE) which is caused by the solid-solid, diffusion-less phase transformation known as martensitic transformation. Most of the applications and/or, researches on this functional material have been mainly centered to its property of SE, that enables the material to recover the original shape from the largely deformed state when the mechanical load, which causes the deformation, is withdrawn. Besides this unique property, however, the peculiar stress-strain curves beyond the stress-induced martensitic transformation (SIMT) region also need careful attention with the view of investigating on the large deformation of the structural elements made of the same material.

With this perspective, mechanical behaviors of the columns and shafts made of superelastic SMA have been investigated considering a few loading-unloading cycles in order to demonstrate and analyze some unique and important characteristics. Additionally, a unique phenomenon that occurs during tensile test of the superelastic SMA specimen has been examined and discussed.

The interpretations of the mechanical behaviors of the structural elements made of superelastic SMA are closely related with the important material properties, that is, its stress-strain curves and the SIMT. Therefore, at first, rigorous tests were performed to study the behaviors of the superelastic SMA (Ti49.3 at% Ni50.2at% V0.5at%) specimens in tension and compression. For comparison, tests were also carried out for the Al and the stainless steel (SUS304) specimens under similar test conditions. Results show that the Al has the lowest yield strength, while for large strains after the SIMT the SMA can carry the highest load. Moreover, both Al and SUS304 exhibit more or less the similar nature of stress-strain curves in compression and tension. On the other hand, the compressive strength of the superelastic SMA is significantly higher than its tensile strength, particularly for large strains. Furthermore, unlike the tensile stress-strain curve there is no distinct plateau for a particular range of strains and as such, the start and finish points of the SIMT process are rather difficult to identify for the compressive stress-strain curve. It appears, for the compression test, the SIMT process is indicated by a slight change in slope of the stress-strain curve.

CHAPTER 2 Buckling and Postbuckling Characteristics of the Superelastic SMA Columns-Experiment and Qualitative Analysis of the Results

In this work, buckling and postbuckling behaviors of the superelastic SMA columns are observed for a wide range of slenderness ratio (*L/k*) and compared with those of the SUS304 and Al columns under similar test conditions. The experimental method is comprised of compressive loading on the columns much beyond the point of instability, followed by unloading allowing them to recover the shapes. It is found from the load-deformation curves that among the three materials, the buckling load of the SMA column increases most significantly with the decreasing value of *L/k* and ultimately exceeds that of SUS304 column. A few more phenomena have also been observed as delineated below.

Contrary to the general notions, experimental observations verify that upon too large deformation (far beyond the first point of instability), the shortest SMA column (*L/k*=28) shows a distinct and highly stable secondary mode of deformation. More astonishingly, the short column (*L/k*=38) shows two distinct peak loads, the second peak being higher than the first one. For a few consecutive loading-unloading cycles, these short SMA columns have much higher buckling loads but the smallest cumulative residual strains, in comparison with the SUS304 and Al columns. On the other hand, the slender superelastic SMA columns also show a few unique behaviors. For example, the magnitude of load is least changed during the postbuckling compression and in some cases the load (recovery force) increases during unloading of the buckled column. The shape is almost fully recovered upon unloading.

Qualitative analysis has been performed to explain the above phenomena with the help of the fundamental properties of the column materials, that is, the SIMT and the stress-strain curves in compression and tension. It can be concluded that the slender SMA column buckles in the austenite phase and because of the low material stiffness, its buckling load is lower than that of a slender Al column. On the other hand, too short SMA column buckles plastically after the maximum strain in the column material exceeds the region of SIMT. Because of SMA's too high strength after the SIMT, short SMA column's buckling load exceeds that of the SUS304 column. In can be concluded that the peculiar nature of the stress-strain curve together with the SE enable the SMA columns to exhibit such unique behaviors.

CHAPTER 3 Buckling and Postbuckling Characteristics of the Superelastic SMA Columns-Numerical Simulation

For precise quantitative analysis of the unique performances of the superelastic SMA columns as demonstrated by experimental results, numerical solution was carried out. Stress-strain relations have been determined from pure compressive and tensile test data for sufficiently large strains, and used in the analysis. Static analysis was performed considering large deflection option and those nonlinear stress-strain relations. The commercial FEM code ANSYS has been used for the simulation. Three suitable material models, namely, Multilinear isotropic hardening (MISO), Multilinear elastic (MELAS) and Hyperelastic (Mooney-Rivlin) were used for simulation.

Simulation was also carried out to predict the buckling and postbuckling behaviors for the SUS304 columns. The MISO model takes into account the plasticity effect and is suitable to simulate the complete loading-unloading cycle for the SUS304 column. The MELAS model considers nonlinear elasticity and was used to simulate the unloading path of the buckled SMA column. The Hyperelastic (Mooney-Rivlin) model was used to predict the behaviors of the short SMA columns.

Comparison shows, for a very wide range of slenderness ratio (28-318), the predicted behaviors of the SMA and SUS304 columns agree well with those of the experimental results. It is also found that the tensile stress-strain data could be used to predict the behaviors of the SUS304 columns and the slender SMA columns.

Because of used SMA's significant asymmetry of the tensile and compressive stress-strain curves (for large values of strains), however, the compressive stress-strain curve is vital to analyze the load-deformation curves, in particular, for the short SMA columns. Simulation results verify that for those columns, most of the column material remains under compression even after buckling. The maximum compressive strains exceed the range of SIMT. It is verified that there is a point of instability after which the shortest SMA column has a stable postbuckling configuration.

Simulation results show that at the critical point of the load-deformation curve, the maximum compressive strains remain within a small value for the slender columns, meaning they buckle in the austenite phase. However, it is important to note that during the postbuckling compression, the strain becomes large even for the slender columns. Because of SMA's high compressive strength for large strains, the slender column can sustain the load with least change in magnitude.

To simulate the remarkable phenomenon that the recovery force increases during unloading of the slender SMA columns, a special method has been developed to trace the continuous unloading path of the buckled columns. It is found that defining a few intermediate unloading curves between the actual loading and the unloading curves can help to minimize stress discontinuity at the beginning of unloading. It can be concluded that the recovery force increases because of elastic shape recovery of the slender SMA column.

CHAPTER 4 Behaviors of the Superelastic SMA Shafts under Torsion

Under torsional loading, superelastic SMA shafts could be subjected to strains far beyond the pure elastic limit. Therefore, several experiments were carried out to study the behaviors of the solid and hollow shafts under torsion for different unsupported lengths and angles of twist. Experimental evidence reveals the fact that if the angle of twist is not too large, the SMA shaft makes a much narrower hysteresis than that of the SUS304 shaft, under loading-reverse loading cycles. In general, the hollow superelastic SMA shaft makes a similar but narrower hysteresis, and fails at a lower angle of twist in comparison with the solid shaft.

The most important characteristic of the SMA shaft is that its torsional strength increases nonlinearly and exceeds that of the SUS304 shafts for increasing value of the angle of twist. Buckling is usually caused by compression; but a shaft may also become unstable under the action of a torque. Consequently, when the torque exceeds a critical value (that can be found by theoretical calculation), the slender SMA shafts are found to buckle like a column. During experiments, pictures were taken to observe the change in the shape of the slender shafts at different values of torque. Simultaneously, the torque-angle of twist curve was observed. It is found that the SMA shafts buckle in the vicinity of the theoretical buckling torque. The observed buckling torque is found to vary linearly with the unsupported length of the shafts. On the other hand, after the initial portion of the torque-angle of twist curve, the torque increases too slowly for increasing value of the angle of twist for the SUS304 shafts. Moreover, the critical twisting moment for the SUS304 shaft is more than thrice of the SMA shaft. As a result, usually, material failure is likely to occur before a slender SUS304 shaft buckles.

Slender tubular SMA shafts also buckle under torsion but shows better shape recovery upon unloading. Observation shows that the superelastic SMA shaft behaves like a fibrous material (for instance, rope) under torsion as distinct twisting wrinkles appear on the surface of the tubular shaft which cause its failure.

CHAPTER 5 Discussions and Conclusions

Conclusions are made on the overall work of Chapters 1- 4, after discussions.

APPENDIX A Direct Method to Estimate Stress-Induced Martensitic Transformation Points by Tensile Test

This study deals with a unique phenomenon that occurs during the SIMT for a superelastic SMA rod under tension test. Deformations of the specimen were measured simultaneously by the displacements of the fixture and also by strain gage. Strain gage gives reading of the local strain while the fixture displacement gives reading of the overall strain of the specimen. It is found, as the SIMT is initiated, there is no local strain although there is end displacements! Local displacements start again after the SIMT is over. Thus, the SIMT start and finish points can be observed by plotting the data of strain gage reading versus the end displacement reading. The same phenomenon is observed during unloading when the reverse phase transformation occurs.

Examinations show that, in the test specimen, the SIMT and reverse SIMT start locally at different values of stress, which accounts for the above phenomena. It is found that the critical stress required to initiate the SIMT for the mid-portion of the specimen is higher than that for the region near the loading end. As a result, the SIMT at first initiates near the loading end and propagates towards the middle portion with the increasing value of the stress and strain.

APPENDIX B Stability Analysis of Eccentrically Loaded Slender Columns Actuated by Shape Memory Alloy Wires

In this study, experiment was carried out to investigate on the stability of a slender steel column with known eccentricity in loading. The column is subjected to high environmental temperatures as well as mechanical load. The pre-strained SMA wires can act as thermal actuators when heated above the austenite finish temperature. Therefore, they were externally attached with the columns and the effect of their actuating force on the buckling behaviors of the columns is observed. It is found, above certain temperature, the buckling load and the shape of the column can be changed because of the actuating force of the SMA wires.

論文審査結果の要旨

構造部材として形状記憶合金を用いる場合には、その超弾性挙動を明らかにしておく必要があるが、まだ殆ど明らかになっていない。本論文では、圧縮と捩り荷重を受ける形状記憶合金円柱の応力誘起マルテンサイト変態による超弾性挙動を明らかにし、座屈後の特異な大変形挙動を見つけ出し、その原因を解明している。本論文は、これらの研究成果をまとめたもので全編5章よりなる。

第1章は序論である。

第2章では、超弾性形状記憶合金円柱の圧縮座屈と座屈後の実験を行い、多くの新知見を得ている。即ち短い円柱では鉄鋼製より高い座屈荷重を示し、長い円柱では座屈後急激に耐荷重が低下しないことを明らかにしている。また、座屈後に発生する大変形は除荷後殆ど消滅することを明らかにしている。更に荷重を繰り返し加えても残留変形は非常に小さいことを明らかにしている。これらは貴重な知見である。

第3章では、形状記憶合金の引張り圧縮試験により得られた非線形応力歪曲線に基づき、超弾性形状記憶合金円柱の圧縮座屈と座屈後の挙動を有限要素法で数値シミュレーションし、実験と一致する結果を得ている。これにより座屈の特異現象の理論的裏付けが明らかになり、これは有用な成果である。

第4章では、超弾性形状記憶合金円柱の捩り荷重と捩り角の関係を明らかにすると共に、長い円柱では高い捩り荷重と大きな捩り角の範囲で曲げ変形が発生し、座屈現象が起きることを明らかにしている。また座屈後に発生する大変形は除荷後殆ど消滅することを明らかにしている。更に中空円柱では捩り座屈荷重が低下するが、除荷後の残留歪は非常に小さいことを示している。これらは重要な知見である。

第5章は結論である。

以上要するに本論文は、圧縮と捩り荷重を受ける超弾性形状記憶合金円柱の座屈と座屈後の挙動は鉄鋼円柱とは全く異なることを明らかにしたもので、機械工学の発展に寄与するところが少なくない。

よって、本論文は博士（工学）の学位論文として合格と認める。